Chapter 10

Detection of Accelerating Transient of Aseismic Rock Strain using Precursory Decline in Groundwater Radon

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Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/59530

1. Introduction

A seismic slip can be preceded by accelerating aseismic slips near the hypocenter of an impending earthquake. Compared with the strain step recorded at the time of the earthquake, the precursory strain from aseismic fault slips are transient and small. It is of practical interest to be able to detect the accelerating aseismic rock strain for the warning of local disastrous earthquakes. From a series of laboratory experiments in un-drained conditions, I discovered a significant drop in groundwater radon, greater than 50 %, by a mechanism of radon volatilization into the vapor phase. Both radon volatilization and rock dilatancy offer attractive in-situ physical mechanisms for a premonitory decrease in groundwater radon. In addition, we have been monitoring groundwater radon at well (D1) in the Antung hot spring in eastern Taiwan since July 2003 (Fig. 1). The Antung hot spring is located near the Chihshang fault that ruptured during two 1951 earthquakes of magnitudes M=6.2 and M=7.0 (Hsu, 1972). Based on the long-term observation at the Antung hot spring, I discovered that an un-drained brittle aquifer near an active fault can be used as a natural strain meter for detecting recurrent precursory radon declines. The observed radon minimum decreases as the earthquake magnitude increases. The un-drained condition at well (D1) is essential for the development of two phases (vapor and water) in the rock cracks, which is attributed to the happening of recurrent precursory radon declines. The concurrent concentration declines in groundwater-dissolved gases (radon, methane, and ethane) support the un-drained condition at well (D1) and the mechanism of in-situ volatilization of groundwater-dissolved gases. Radon precursory declines in groundwater can only be detected in certain locations with favorable geological conditions. An un-drained brittle aquifer near an active fault is recommended to monitor recurrent precursory radon declines. The objective of this chapter is to provide a practical means to detect the accelerating aseismic rock strain using the precursory decline in groundwater radon. A case study is provided in this chapter to illustrate the application of an undrained brittle aquifer as a natural strain meter to detect the accelerating transient of aseismic rock strain by monitoring precursory decline in groundwater radon.

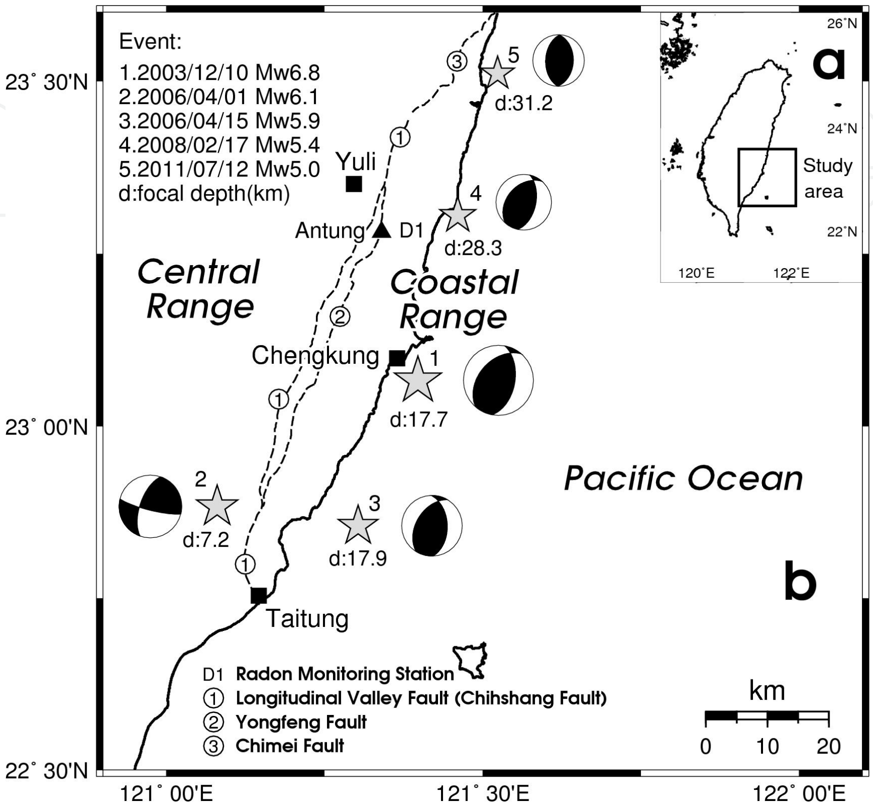

Figure 1. Map of the epicenters of the earthquakes that occurred on December 10, 2003, April 1 and 15, 2006, February 17, 2008, July 12, 2011 near the Antung hot spring. (a) Geographical location of Taiwan. (b) Study area near the Antung hot spring (filled stars: mainshocks, filled triangle: radon-monitoring station).

2. Monitoring methods

We have been monitoring groundwater radon at a well (D1) located at the Antung hot spring in eastern Taiwan since July 2003. Figure 1 shows that the radon-monitoring well (D1) is about 3 km southeast of the Chihshang fault. Discrete samples of groundwater were pumped and collected from the radon-monitoring well (D1) twice per week for analysis of radon content. We also started to analyze methane and ethane from November 2007 and November 2010, respectively.

The production interval of the radon-monitoring well (D1) ranges from 167 m to 187 m. Water samples were collected in a 40 mL glass vial with a TEFLON-lined cap. To obtain representative water samples for radon, methane, and ethane measurements, a minimum purge of three well-bored volumes were required before taking samples. A minimum of 50 min purging-time was required with a pumping rate at around 200 L/min.

It is important to ensure the radon not to escape during the sampling procedure and the sample transportation and preparation. For every sampling, the sample vial was inverted to check if any bubbles were present in the vial. The sample water with gas bubbles present was discarded and sampling was repeated. The sampling time of sample collection were recorded and radon measurement was done within 4 days. The samples were stored and transported in a cooler to minimize biological degradation of methane and ethane.

The liquid scintillation method was applied to determine the concentration of radon in groundwater [12]. Radon was first extracted into a mineral-oil based scintillation cocktail from the water samples, and then measured with a liquid scintillation counter (LSC). The measurement results were corrected for the radon decay between sampling and counting.

Calibration factor for the LSC measurements should be at least 6 cpm/pCi with the background not exceeding 6 cpm. For a count time of 50 min and background less than 6 cpm, we achieved a detection limit below 18 pCi/L using the sample volume of 15 ml.

The head space method was used to determine the concentrations of methane and ethane in groundwater with a gas chromatograph (Shimadzu GC-14A), a HP-Plot/Q, 30 m, 0.53 mm i.d. capillary column, and a flame ionization detector (FID). The concentrations of methane and ethane measured in the head space were converted to groundwater concentrations using Henry's constants of 31.5 and 23.9, respectively, for methane and ethane at a room temperature of 27 ℃.

3. In-situ radon-volatilization and rock-dilatancy

Radon partitioning into the gas phase can explain the anomalous decreases of radon concentration in groundwater precursory to the earthquakes [7]. Based on radon phase-behavior and rock-dilatancy process [1], [8] developed a mechanistic model to correlate the observed decline in radon with the rock strain precursory to an earthquake. We will present the model with two parts, i.e., the radon-volatilization model and the rock-dilatancy model. The radon-volatilization model which correlates the radon decline to the gas saturation can be expressed as follows.

$$C_0 = C_w (H S_g + 1) \tag{1}$$

where C_0 is the stabilized radon concentration in groundwater before a radon anomaly, pCi/L; C_w is the observed radon decline in groundwater during a radon anomaly, pCi/L; S_g is the gas saturation in aquifer during a radon anomaly, fraction; H is Henry's constant for radon, dimensionless. The Henry's constant (H) at formation temperature (60 ℃) is 7.91 for radon [5].

The rock-dilatancy model which correlates the rock strain to the gas saturation can be expressed as follows.

$$d\varepsilon \cong \phi \ S_g \tag{2}$$

where $d\varepsilon$ is the rock strain precursory to an earthquake, fraction; ϕ is the fracture porosity of aquifer, fraction; S_g is the gas saturation in aquifer during an radon anomaly, fraction.

Based on the radon volatilization and rock dilatancy models, we can correlate the radon decline in groundwater radon to the rock strain precursory to an earthquake. Combining equations (1) and (2), we obtain equation (3) as follows.

$$d\varepsilon \cong \frac{\phi}{H} \left(\frac{C_0}{C_w} - 1 \right) \tag{3}$$

where $\left(\frac{C_0}{C_w} - 1 \right)$ is normalized radon decline precursory to an earthquake, dimensionless. Given the precursory decline in groundwater radon such as, Figure 2, equation (3) can be used to calculate the precursory crustal-strain transient from aseismic fault slips. Case studies are provided to illustrate the application of an un-drained brittle aquifer as a natural strain meter to detect the accelerating transient of aseismic rock strain by observing premonitory decline in groundwater radon.

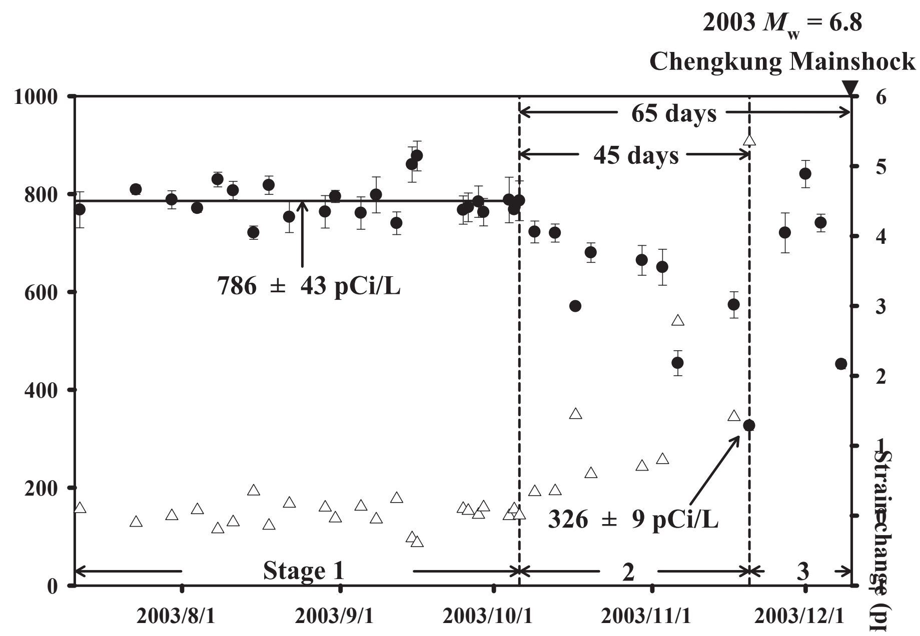

Figure 2. Observed radon decline and calculated crustal-strain transient prior to 2003 M_W 6.8 Chengkung earthquake at the monitoring well (D1) in the Antung hot spring (solid circles: observed radon concentration; open triangles: calculated crustal-strain). Stage 1 is buildup of elastic strain. Stage 2 is development of cracks and gas saturation. Stage 3 is influx of groundwater.

http://dx.doi.org/10.5772/59530

4. A case study

[7] discovered that a significant drop in groundwater radon, greater than 50 %, can be generated in the laboratory by a process of radon volatilization into the gas phase in un-drained conditions. We conducted a series of radon-partitioning experiments to determine the variation of the radon concentration remaining in groundwater at various levels of gas saturation. Figure 3 shows the results of vapor-liquid, two-phase radon-partitioning experiments conducted at formation temperature (60 ℃) using formation brine from the Antung hot spring. The processes of rock dilatancy, under-saturation and radon volatilization offer an attractive mechanism to monitor anomalous radon declines in groundwater radon precursory to an earthquake. Given an observed radon decline precursory to an earthquake, we can apply Figure 3 to estimate the amount of gas saturation in micro-cracks developed in aquifer during an radon anomaly. For example, a gas saturation of 10 % in cracks developed in the aquifer rock when the radon concentration in groundwater decreased from 780 pCi/L to 330 pCi/L precursory to the 2003 M_w 6.8 Chengkung earthquake. [16] reported that the fracture porosity for naturally fractured rocks ranges from 0.00008 to 0.0003. To generate an in-situ gas saturation of 10% in a fractured aquifer, a crustal strain of 8.0 ppm and 30.0 ppm is required for a fracture porosity of 0.00008 and 0.0003, respectively. Both low-porosity and un-drained conditions are favorable for applying a fractured aquifer as a natural strain meter by monitoring precursory decline in groundwater radon. It is of practical interest to be able to detect the accelerating aseismic rock strains by monitoring the radon concentration in groundwater.

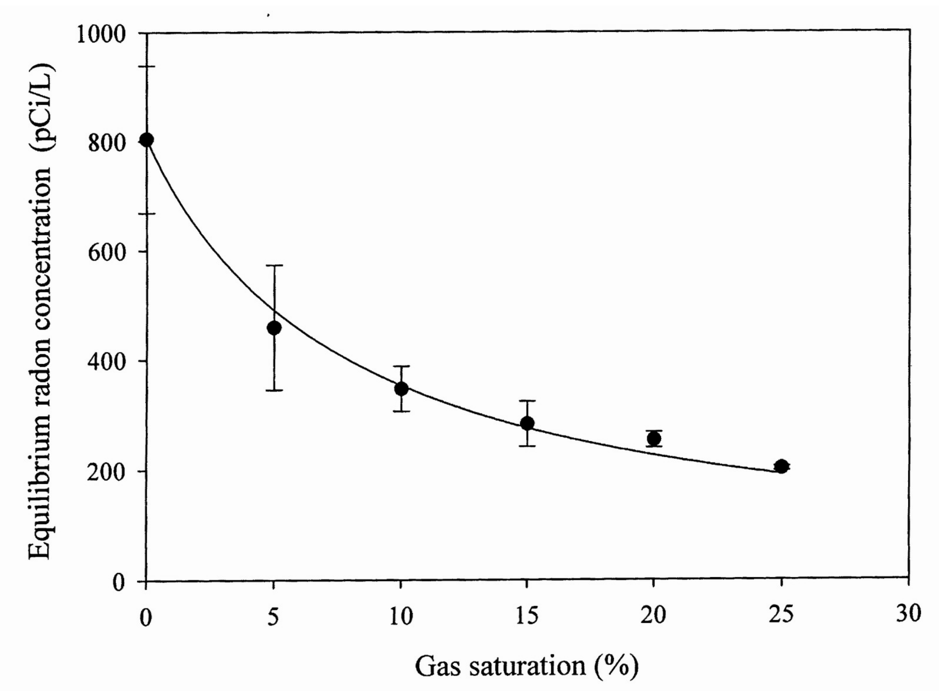

Figure 3. Variation of radon concentration remaining in groundwater with gas saturation at 60℃ using formation brine from the Antung hot spring.

Since July 2003, we have observed recurrent recurrent anomalous declines in groundwater radon at the Antung well (D1) in eastern Taiwan precursory to the 2003 M_w = 6.8 Chengkung, 2006 M_w = 6.1 Taitung, 2008 M_w = 5.4 Antung, and 2011 M_w = 5.0 Chimei earthquakes that occurred on December 10, 2003, April 1, 2006, February 17, 2008, and July 12, 2011, respectively. The epicenters of the 2003 M_w = 6.8, 2006 M_w = 6.1, 2008 M_w = 5.4, and 2011 M_w = 5.0 earthquakes were located only 24 km, 52 km, 13 km, and 32 km, respectively, from the observation well (D1).

The observed radon anomalies can be correlated with the magnitude and precursor time of upcoming earthquakes. We define the precursor time for radon as the time interval between the moment when the trend of the radon concentration starts to decline and the time of occurrence of the earthquake. Based on the radon anomalies observed prior to (1) 2003 M_w 6.8 Chengkung, (2) 2006 M_w 6.1 Taitung, (3) 2008 M_w 5.4 Antung, and (4) 2011 M_w 5.0 Chimei earthquakes, Table 1 summarizes the precursor time and radon minima. [11] shows that as the magnitude of earthquakes increases, the precursor time for radon anomalies increases and the observed radon minima decrease. Monitoring precursory decline in groundwater radon at a suitable geological site can be a useful means of forecasting the magnitude and precursor time of local disastrous earthquakes.

Earthquake	**Moment magnitude, M_W, *(dimensionless)***	**Precursory time (day)**	**Radon minimum (pCi/L)**
2003 Chengkung	6.8	65	326 ± 9
2006 Taitung	6.1	61	371 ± 9
2008 Antung	5.4	56	480 ± 43
2011 Chimei	5.0	54	447 ± 18

Table 1. Observed precursory time and radon minimum at well (D1) prior to (1) 2003 M_W = 6.8 Chengkung, (2) 2006 M_W = 6.1 Taitung, (3) 2008 M_W = 5.4 Antung, and (4) 2011 M_W = 5.0 Chimei earthquakes.

[4] show that the Antung hot spring situated in an andesitic block and surrounded by a ductile mudstone of the Lichi mélange. Figure 4 shows the geological map and cross section near well (D1) in the area of Antung hot spring which is a low-porosity fractured confined aquifer. The groundwater is in un-drained conditions at well (D1). [13] and [15] suggested that the development of new cracks in aquifer rock could occur at a rate faster than the recharge of pore water in un-drained conditions. Gas saturation developed in the rock cracks and groundwater-dissolved radon then volatilized into the gas phase. We also observed simultaneous anomalous declines in groundwater-dissolved radon and methane precursory to the 2008 M_w = 5.4 Antung earthquake [9]. The mechanism of in-situ radon volatilization was substantiated.

The composition of groundwater-dissolved gases taken from a separator flow test at well (D1) on December 26, 2006 consists of 62.8 % of nitrogen, 36.7 % of methane, and 0.5 % of ethane

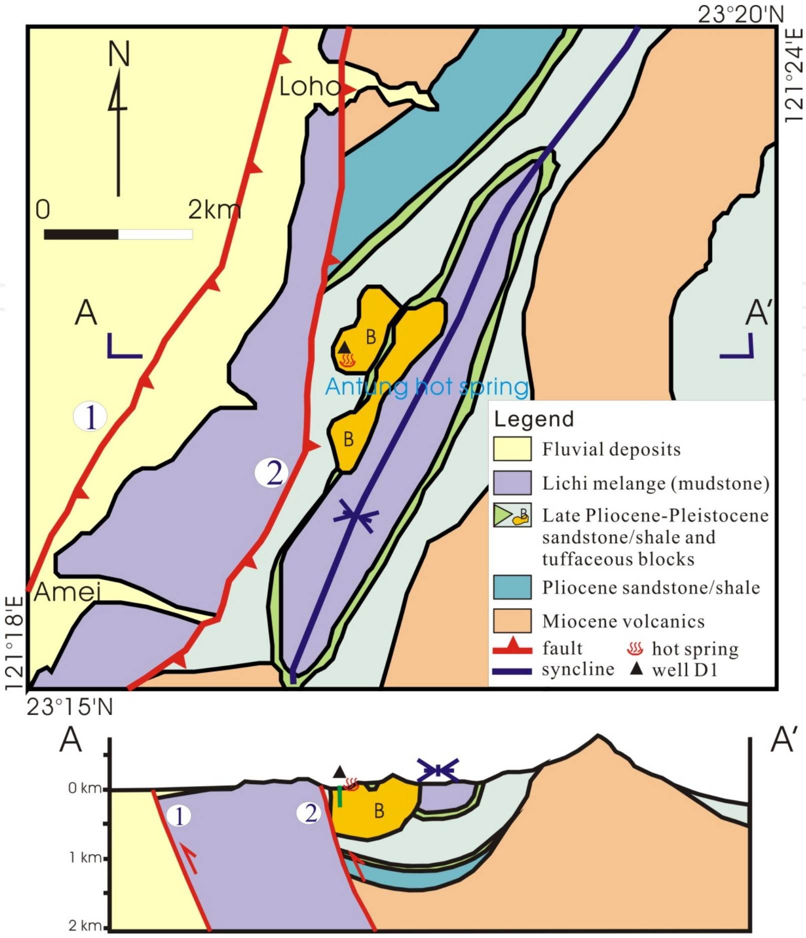

Figure 4. Geological map and cross section near the radon-monitoring well (D1) in the area of Antung hot spring. (B: tuffaceous andesitic blocks; 1): Chihshang, or, Longitudinal Valley Fault, 2): Yongfeng Fault)

by volume. In addition to radon and methane, we initiated the monitoring of groundwater-dissolved ethane at well (D1) in the Antung hot spring since November 30, 2010 to corroborate the in-situ volatilization mechanism. The in-situ radon-volatilization model for groundwater-dissolved radon, methane, and ethane can be expressed as follows.

$$C_{0,Rn} = C_{w,Rn}(H_{Rn}S_g + 1) \tag{4}$$

$$C_{0,Me} = C_{w,Me}(H_{Me}S_g + 1) \tag{5}$$

$$C_{0,Et} = C_{w,Et}(H_{Et}S_g + 1) \tag{6}$$

where $C_{0,Rn}$ is the stabilized radon concentration in groundwater before a radon anomaly, pCi/L; $C_{w,Rn}$ is the observed radon decline in groundwater during a radon anomaly, pCi/L; S_g is the gas saturation in aquifer during a radon anomaly, fraction; H_{Rn} is Henry's constant for radon, dimensionless; $C_{0,Me}$ is the stabilized methane concentration in groundwater before a methane anomaly, mg/L; $C_{w,Me}$ is the observed methane decline in groundwater during a methane anomaly, mg/L; H_{Me} is Henry's constant for methane, dimensionless; $C_{0,Et}$ is the stabilized ethane concentration in groundwater before a ethane anomaly, mg/L; $C_{w,Et}$ is the observed ethane decline in groundwater during a ethane anomaly, mg/L; H_{Et} is Henry's constant for ethane, dimensionless. The Henry's coefficients at 60 °C are 7.91, 37.6, and 38.2 for radon, methane, and ethane, respectively. According to equations (4), (5), and (6), the mechanism of in-situ volatilization predicts the concurrent concentration declines in groundwater-dissolved radon, methane, and ethane.

Prior to the 2011 Chimei earthquake, the concurrent concentration declines in groundwater-dissolved radon, methane, and ethane were observed [10]. Figure 5 shows the observed concentration anomalies for radon, methane, and ethane, respectively, precursory to the 2011 Chimei earthquake. The concentration errors are ±1 standard deviation after simple averaging of triplicates. Radon, methane, and ethane decreased from background levels of 752 ± 24 pCi/L, 8.24 ± 0.48 mg/L, and 0.217 ± 0.010 mg/L to minima of 447 ± 18 pCi/L, 5.81 ± 0.30 mg/L, and 0.161 ± 0.008 mg/L, respectively (Figure 5). The mechanism of in-situ radon volatilization was confirmed again by the simultaneous anomalous declines in groundwater-dissolved radon, methane, and ethane.

The anomalous decline of radon concentration in groundwater was observed prior to the 2003 Chengkung earthquake. Figure 2 shows that the sequence of events can be divided into three stages. During Stage 1 (from July 2003 to September 2003), radon concentration in groundwater was fairly stable (around 780 pCi/L). During Stage 1, there was a slow, steady increase of effective stress and an accumulation of tectonic strain. Sixty-five days before the 2003 $M_w = 6.8$ Chengkung earthquake which occurred on December 10, 2003, the concentration of radon started to decrease and reached a minimum value of 330 pCi/L twenty days before the earthquake. We define this 45-day period as Stage 2. Dilation of the rock mass occurred during Stage 2. When the aquifer is in un-drained conditions, the development of new cracks in aquifer rock could occur at a rate faster than the recharge of pore water. Gas saturation then developed in the rock cracks and groundwater-dissolved radon volatilized into the gas phase. After the minimum point of radon concentration (Stage 3), groundwater continued to encroach into the rock cracks and the water saturation in the aquifer began to increase. During Stage 3, groundwater-dissolved radon increased and recovered to the background level. The main shock produced a sharp coseismic anomalous decrease (~300 pCi/L).

The 2003 Chengkung earthquake's dislocation fault model was analyzed by Wu et al using a computer code by [14]. [17] determined the fault geometry utilizing aftershock distribution and geology (CGS 2000a, b) and assumed a thrust fault parallel to Coastal Range with strike N20˚E, with a bend at a depth of 18 km. The fault-plane dips 60˚SE and 45˚SE above and below 18 km respectively. Assume both the lower and upper fault-planes extend a maximum of 33 km from north to south. Rupturing of the lower and upper fault-planes occurred within depths of 18-36 km and 5-18 km, respectively. For an optimal fit with the coseismic ground deformation, the lower fault slipped 61.6 cm with a rake of 81.7˚ and the upper fault slipped 26 cm with

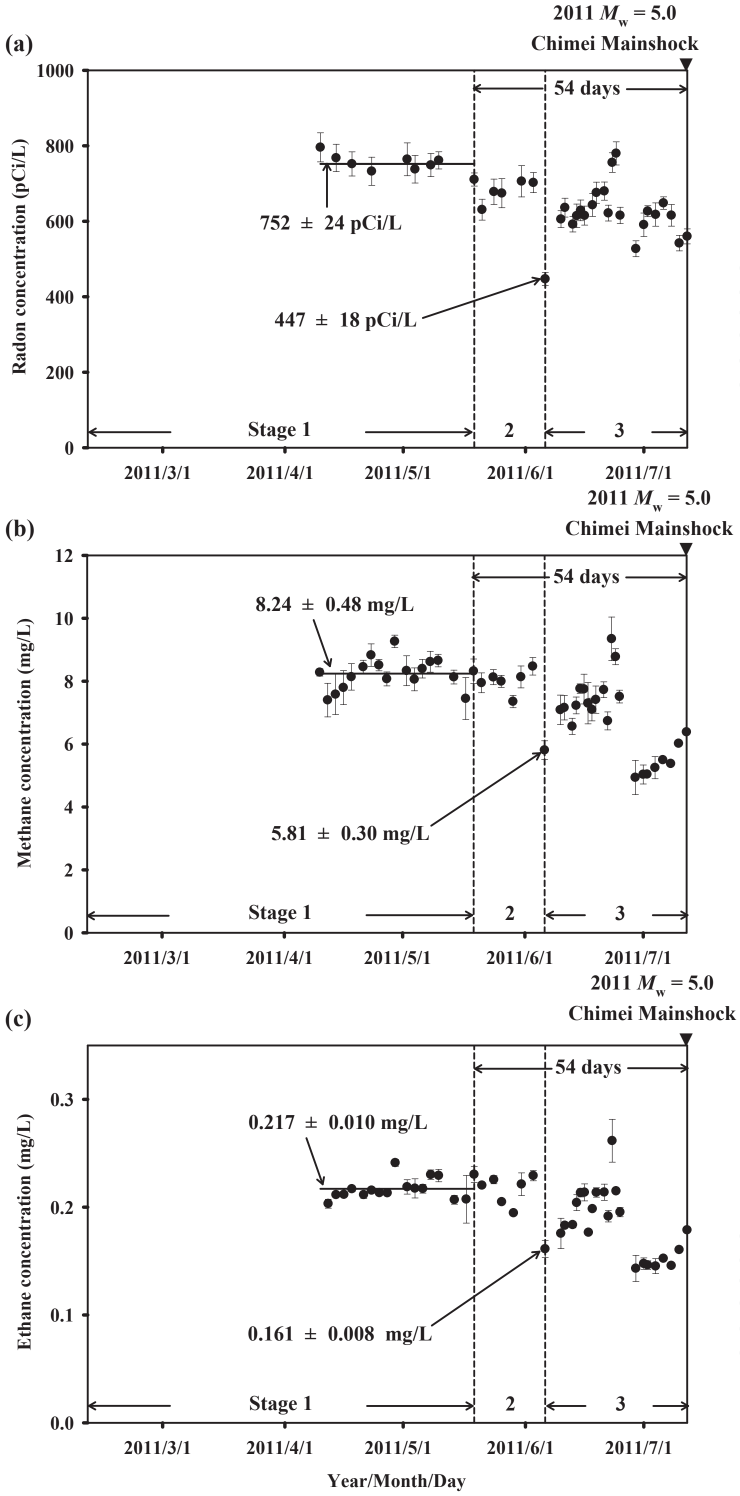

Figure 5. Observed concentration anomalies (a) radon, (b) methane, and (c) ethane prior to 2011 M_W 5.0 Chimei earthquake. Stage 1 is buildup of elastic strain. Stage 2 is development of cracks. Stage 3 is influx of groundwater.

a rake of 47.3°. The area and slip on the ruptured surface of the lower and upper fault-planes were used to calculate M_w (moment magnitude scale), with respective values of 6.7 and 6.3.

The total M_w was about 6.8 and agreed with the result of the moment tensor inversion solution from the Harvard CMT database (http://www.seismology.harvard.edu/), indicating that the coseismic energy were mainly released by the lower fault. Coseismic strain distribution due to the 2003 Chengkung earthquake was calculated using the dislocation fault model [17] and a computer code by [14]. Contraction surface strain near the Antung hot spring area was approximately 20 ppm (Fig. 6).

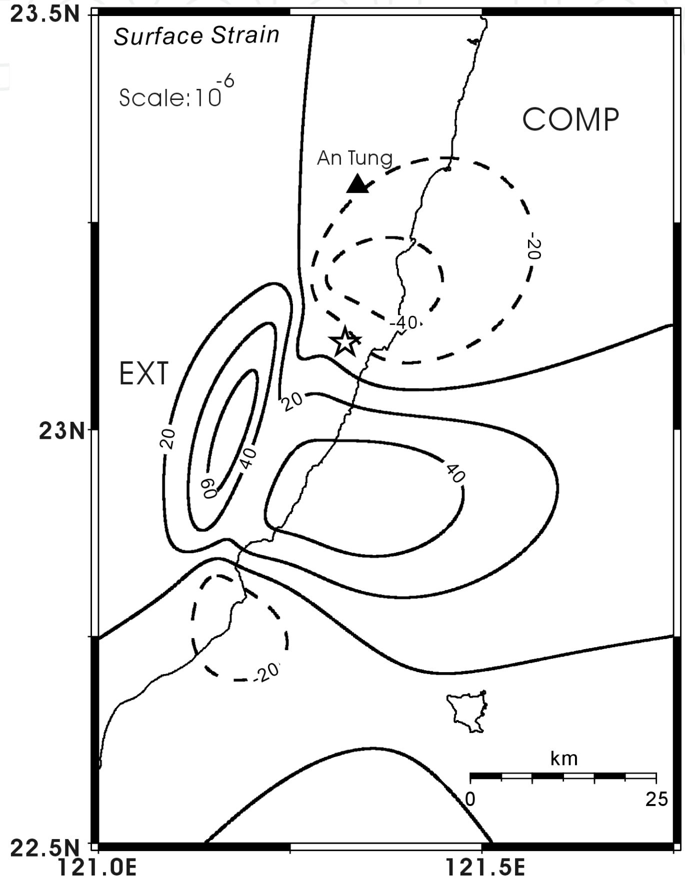

Figure 6. Distribution of coseismic surface strain (ppm) calculated based on the computer code for dislocation models by [14]. Positive and negative values mean dilatation and contraction, respectively. The open star denotes the 2003 mainshock. The filled triangle denotes the radon-monitoring well (D1). EXT and COMP denote dilatation and contraction, respectively.

A seismic slip can be preceded by accelerating aseismic slips near the hypocenter of an impending earthquake. Compared with the strain step about 20 ppm at the time of the 2003 Chengkung earthquake, the precursory strains from aseismic fault slips are small and accelerating. It is of practical importance to detect the accelerating transient of aseismic rock strain for the warning of local disastrous earthquakes. With the help of a case study, we show the capability to monitor the precursory decline in groundwater radon and to detect the accelerating transient of aseismic rock strain prior to the 2003 M_w = 6.8 Chengkung earthquake. Based on the precursory decline in groundwater radon observed at the Antung hot spring (Fig. 2), equation (3) can be used to calculate the accelerating transient of crustal-strain from aseismic

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fault slips prior to the 2003 M_w = 6.8 Chengkung earthquake. The open triangles in Fig. 2 show the calculated crustal-strain transient prior to 2003 M_W 6.8 Chengkung earthquake at the monitoring well (D1) in the Antung hot spring with an average fracture porosity of 0.00003.

5. Conclusions

In a series of laboratory experiments in un-drained conditions, I discovered a significant drop in groundwater radon, greater than 50 %, by a mechanism of radon volatilization into the gas phase. In-situ radon volatilization offers an attractive mechanism for a premonitory decrease in groundwater radon. An un-drained brittle aquifer near an active fault can be employed as a natural strain meter for detecting recurrent precursory radon declines. Anomalous declines in groundwater radon consistently recorded at a well (D1) prior to large earthquakes on the Chihshang fault in eastern Taiwan provide the reproducible evidence. Compared with the coseismic strain, the precursory strain from aseismic fault slips are transient and small. In this chapter, a quantitative method using the precursory radon decline as a tracer to detect the accelerating aseismic rock strain is presented with the help of a case study.

Acknowledgements

Supports by the National Science Council (NSC-103-2116-M-006-013), Central Geological Surveys, Industrial Technology Research Institute (L550001060), Radiation Monitoring Center, and Institute Earth Sciences of Academia Sinica of Taiwan are appreciated.

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